APPLICATION FOR UNITED STATES PATENT

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for

MICRO-CAVITY LASER

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S P E C I F I C A T I O N

This application claims priority on United States provisional application No. 60/188,325, filed March 9, 2000, and entitled, "Fiber-Coupled Microsphere Laser." The disclosure of the foregoing is incorporated by reference herein as if set forth in full hereat.

FIELD OF INVENTION

The field of the invention relates to lasers and certain related methods, and in particular to micro-cavity lasers and related methods.

BACKGROUND OF THE INVENTION

In the now rapidly expanding technology relating to the use of optical waveguides and in particular fiber optic waveguides, a number of discrete devices and subsystems have been developed to modulate, route or otherwise control, optical beams that are at specific wavelengths. Present day communication systems increasingly use individual waveguides to carry densely wavelength multiplexed optical beams. Thus, there is a need for a self-contained device and related methods which can induce a lased output in a frequency range of interest. Currently, the telecommunications industry uses frequencies in the 1550 nm range.

It is known to one of ordinary skill in the art how to couple a waveguide to an optical resonator so as to transfer optical power to the resonator from the waveguide or from the waveguide

to the resonator. It is also known to one of ordinary skill in the art that power circulates in a resonator preferentially at resonant frequencies corresponding to optical modes of the resonator. For the purposes of discussion the terms resonance and optical mode will be used interchangeably herein. Likewise the principles associated with lasing action in resonators and in particular rare earth doped resonators and micro-resonators are well understood to one of ordinary skill in the art. The terms micro-cavity, resonator, micro-resonator will be used interchangeably herein. Discussion of these concepts can be found in one or more of the following references, the disclosure of each of which is incorporated by reference herein as if set forth in full hereat: V. Lefevre-Seguin and S. Haroche, Mater. Sci. Eng. B**48,** 53 (1997); J. C. Knight, G. Cheung, F. Jacques, and T. A. Birks, Opt. Lett. **22,** 1129 (1997); M. Cai, O. Painter, and K. Vahala, Phys. Rev. Lett. **85,**74 (2000); M. Cai and K. Vahala, Opt. Lett. **25,** 260 (2000); V. Sandoghdar, F. Treussart, J. Hare, V. Lefevre-Seguin, J. M. Raimond, and S. Haroche, Phys. Rev. A **54,** 1777 (1996); W. von Klitzing, E. Jahier, R. Long, F. Lissillour, V. Lefevre-Serguin, J. Hare, J. M. Raimond, and S. Haroche, Electron. Lett. **35,** 1745 (1999); P. Laporta, S. Taccheo, S. Longhi, O. Svelto, and C. Svelto, Opt. Mater. **11,** 269 (1999); V. B. Braginsky, M. L. Gorodetsky, and V. S. Ilchenko, Phys. Lett. A **137,** 393 (1989); A. Serpenguzel, S. Arnold, and G. Griffel, Opt. Lett.**20,** 654 (1995); V. S. Ilchenko, X. S. Yao, and L. Maleki, Opt. Lett. **24,**723 (1999); M. L. Gorodetsky and V. S. Ilchenko, J. Opt. Soc. Am.B **16,** 147 (1999); T. Baer, Opt. Lett. **12,** 392 (1987); G. H. B. Thompson, *Physics of Semiconductor Laser Devices* (Wiley, New York, 1980); T. Mukaiyama, K. Takeda, H. Miyazaki, Y. Jimba, and M. Kuwata-Gonokami, Phys. Rev. Lett. **82,** 4623 (1999);

The theoretical concept of inducing lasing action in a micro-resonator doped with Nd is discussed by F. Treussart, et al., in Eur. Phys. J. D **1**, 235 (1998), the disclosure of which is incorporated by reference herein as if set forth in full hereat. This reference, however, presents a device which relies on the use of prisms to couple to the laser resonator. Such a configuration presents many difficulties and limitations on its use in the field, as it requires delicate and precise alignment, is bulky and not easily adaptable common use and does not produce an output frequency which is currently of most use in the telecommuting industry. Additional limitations of these and other devices include low emission and coupling efficiencies.

The present invention overcomes these and the other limitations of the prior art by providing a compact, self-containable laser source that is directly coupled to an optical fiber waveguide. Optical fibers, in addition to being very important in modern optical communications systems, provide a very convenient means to convey both optical pump power to the laser as well to convey emitted laser radiation from the laser resonator. The ability to directly couple laser emission to an optical fiber is therefore of great practical significance. The output frequency of the present invention can be tuned both by design (based on choice of certain materials and/or dopants utilized) and dynamically (by varying the frequency of the laser pump signal) and by incorporation of grating structures into the micro-cavity. The present invention also provides a laser source with improved emissions and increased coupling efficiency between the waveguide and the resonator. Finally, the each of the preferred embodiments can be made to be robust and easy to implement in a variety of configurations and uses.

SUMMARY OF THE INVENTION

The present invention is directed to a micro-cavity laser and certain related methods. The devices and methods of the present invention are useful for creating laser signals having a frequency within a desired range by optically coupling an optical pump signal in a waveguide to a micro-cavity optical resonator, which resonator includes an active medium which is capable of providing optical gain upon pump excitation and which resonator and pumped active medium result in lasing action at a frequency within the desired output range. In the preferred embodiments, the waveguide is a fiber waveguide of any configuration and the coupling between the fiber waveguide and the resonator is by means of an optical couple between a fiber taper in the fiber waveguide and the micro-cavity optical resonator. In the preferred embodiment the fiber waveguide serves to both transport optical pump power to the resonator to excite the amplifying medium as well as to collect lasing emission from the laser cavity and transport it to elsewhere. The fiber waveguide and the resonator are preferably critically coupled at the pump wavelength so as to maximize pump power coupling to the active medium. In addition, it is possible and important to phase match the fiber taper and the micro-cavity resonator so as to maximize the coupling efficiency between these two elements of the present invention.

In another embodiment two fiber waveguides are coupled to the micro-cavity and each is optimized for coupling of pump power or collection of laser emission. In this embodiment phase matching could be employed to perform this optimization.

The micro-cavity optical resonator can have a variety of shapes including, without limitation, a microsphere, one or more micro-rings, racetracks or disks incorporated on a substrate or one or more micro-rings or disks formed on the fiber waveguide itself. Indeed, it is preferable in certain applications for there to be more than one micro-cavity resonator on a single fiber waveguide, for example in creating a multi-wavelength laser array along the fiber waveguide.

The output of the micro-cavity laser of the present invention can be tuned by varying the pump wavelength and/or utilizing different material composition for the micro-cavity optical resonator. In addition, internal structures such as optical gratings can be added to the optical path within the resonator so as preferentially select a particular optical mode for lasing and in turn the frequency. The laser can also be made to operate continuous wave or self-pulsing.

Accordingly, it is an object of the present invention to provide a micro-cavity laser having the advantages detailed herein.

This and other objects of the invention will become apparent to those skilled in the art from a review of the materials contained herein.

BRIEF DESCRIPTION OF THE DRAWINGS

The accompanying drawings, which are incorporated in, and constitute a part of the Specification, illustrate presently known preferred embodiments of the present invention, and together with the proceeding general description and the following Detailed Description, explain the principles of the invention.

In the drawings:

FIGURE 1 is an illustration of a micro-cavity laser of the present invention;

FIGURE 2 is a plan view illustration of a fiber taper and a micro-cavity resonator;

FIGURE 3 is an image of a fiber taper in contact with the equator of a microsphere resonator;

FIGURE 4 is an illustration of a fiber taper coupled with the equator of a microsphere micro-cavity resonator;

FIGURE 5 is a graph illustrating the phase matching of a fiber taper fundamental mode and a microsphere resonator fundamental modes;

FIGURE 6 is an image of the green-up converted photo-luminescence from a fiber taper-pumped microsphere, where the pump wavelength is tuned close to a fundamental whispering gallery mode;

FIGURE 7 is an image of photo-luminescence spectra [taken at point (a) in Figure 8, below] of a microsphere resonator for an annular pump region about the equator. The photo-luminescence (inset) is taken at point (b) in Figure 8 (with a wavelength range matching that of the main spectra), where the side-mode suppression is 26 dB;

FIGURE 8 is a spectral output of collected laser output power versus absorbed pump power in the microsphere ($L_{out} - L_{in}$). Inset, spectral output of a Fabry-Perot filter, showing the single-mode nature of the micro-cavity laser of the present invention, where for reference a single-frequency laser with a known line-width of 300 kHz is also shown; and

FIGURE 9 shows (a) a single sphere system, and (b) a bi-sphere system in which two spheres have been placed on the same taper and pumped by a single 980 nm laser source, producing two separate laser lines, at 1533 and 1535 nm.

DETAILED DESCRIPTION OF THE INVENTION

Referring hereafter to the figures generally, and in particular to Figures 1-2 here, the present invention is a compact and highly efficient laser 2. In its preferred embodiment, the present invention utilizes transmission media 4; high-Q micro-cavity optical resonators 6; active media associated with the optical resonators to facilitate the lasing of a signal within a frequency band of interest; and, optical pumps to excite the active media. As described below and as will be understood by those skilled in the art, numerous additional implementations of this structure and/or method can be made without departing from the scope or spirit of the invention as described herein.

The transmission media 4 is preferably a fiber waveguide 5 of any type. This includes, without limitation, cylindrical, elliptical, etched, "D"-shape and "panda" fiber configurations as well as polished fiber half-blocks. In the preferred embodiment, a fiber taper 12 is provided in the fiber waveguide 5 between a first and second end of the fiber waveguide 5 as is best illustrated in Figure 2. The tapered sections, 15, 16 and intermediate waist region 14 of the waveguide may be provided, as is known, by stretching the waveguide under controllable tension as it is softened by one or more fixed or movable heat sources (*e.g.*, torches). Commercially available machines can be used for this purpose in production environments. The consequent reduction in diameter of about one or more

orders of magnitude reduces the central core in the core/cladding structure of the optical fiber to vestigial size and function, such that the core no longer serves to propagate the majority of the wave energy. Instead, without significant loss, the wave power in the full diameter fiber transitions into the waist region, where power is confined both within the attenuated cladding material and within a field emanating into the surrounding environment. After propagating through the waist region 14, exterior wave power is recaptured in the diverging tapered region 16 and is again propagated with low loss within the outgoing fiber section 18, as illustrated in Figures 1 and 2.

The high Q resonator 6 in this example is coupled to the externally guided power about the waist region 14 of the waveguide. That is, at all times there is a coupling interaction from the principal fiber into the interior of the resonator 6 via the resonator periphery. The resonator 6 additively recirculates the energy with low loss in the whispering gallery mode ("WGM" or WG mode"), returning a part of the power to the waveguide at the waist 14. When a resonance exists at the chosen wavelength, the resonator 6 functions with effectively total internal reflection and with minimal internal attenuation and radiative losses. However, the emanating portion of the wave power is still confined and guided, so it is presented for coupling back into the waveguide waist 14. Extremely high Q values (as much as 8 billion have been observed) exist in this whispering gallery mode. Different WGM devices can be used for the present invention, including disks, rings, polygons, oblate and prolate spheroids. Furthermore, concentricity or approximate concentricity may in some instances not be necessary, since the WGM effect can exist in non-concentric boundary structures such as ellipses or race-track structures.

In the present invention, the resonator 6 is preferably constructed from a silica material. This provides the advantage of being compatible with many waveguide structures, most importantly, telecommunication fiber waveguides currently in use. Alternatively, resonators can be constructed in a semiconductor, utilizing any of the resonator configurations (*e.g.*, disks, rings, polygons, oblate and prolate spheroids) discussed herein. Depending on the application in which the laser of the present invention might serve and/or the desired frequency bandwidth of the output, the material from which the resonator is constructed may also include one or more additives (for example and without limitation, phosphate) intended to suppress undesirable higher order modes and/or resonances in the resonator 6 at frequencies outside of the desired output bandwidth.

In order for the micro-cavity resonator 6 to lase within a desired frequency bandwidth, an active media must also be present. The active media produces the optical gain necessary to permit lasing once excitation of the structure is initiated by one or more optical pump sources. In the preferred embodiments, the present invention utilizes one or more dopants in the resonator 6 to serve as the active media. The preferred dopants include rare earth materials and particularly erbium, ytterbium, praseodymium, neodymium, holmnium, and thulium, either alone or in combination with another dopant. The exact combination and concentration of dopants depends on the wavelength band or bands sought to be included in the output of the laser of the present invention.

The present invention also utilizes an alignment structure in order to secure the position of the fiber waveguide 6 relative to the micro-cavity resonator 20. Many types of alignment structures are known to those of ordinary skill in the art and may include, without limitation, an etched

substrate or the like. In addition, an alignment structure may include structures of the type disclosed in pending U.S. Patent Application _________, the disclosure of which is incorporated herein in full by reference. Illustrations of these and other embodiments are set forth in Vahala, et al., U.S. Patent Application entitled "Resonant Optical Filters", Serial No. ________, filed February 16, 2001, the disclosure of which is incorporated herein by reference.

To induce a lasing action in the present invention, an excitation signal must be provided to the resonator 6. In the first preferred embodiment, an optical pump 20 is provided to deliver the excitation signal to the resonator 6. Alternative schemes of delivering an excitation sources (*e.g.*, and without limitation, by beam excitation including guided or unguided electrical and/or unguided light beams) can be employed without departing from the scope of the present invention.

Without limiting the foregoing, in the first preferred embodiment an optical pump 20 is optically connected to a first end of the fiber waveguide 5. The optical pump 20 transmits a signal along the waveguide 5 and to the resonator 6 through the fiber taper 12 as discussed above. One or more excited laser signals in the resonator 6 are then communicated to the fiber waveguide 5 propagating both in the direction of the second end of the waveguide as illustrated in Figure 5 (and towards the first end of the waveguide). In an alternative embodiment where the resonator is constructed from a semiconductor, the resonator 6 is preferably pumped by an electrical excitation signal rather than an optical signal, however, pumping in this configuration by a guided or unguided optical or alternative signal beam is also intended to be included within the scope of the present invention.

A significant advantage of the present invention over the work of others is the ability to couple directly to and from optical fiber. Important to this coupling is the ability to "phase match" the fiber taper 12 and the resonator structure 6 to maximize the coupling efficiency. This is done by proper selection of the diameter of the fiber taper 12 at the waist region 14. In so doing, it is possible to match the effective indexes of the fundamental taper mode and the fundamental mode of the resonator 6 (*i.e.*, "phase matching"). As illustrated in Figure 5, where the resonator 6 is a microsphere 7, a 50 micron diameter microsphere 7 phase matches a 1.38 micron diameter fiber taper 12. In the present invention, it is possible to demonstrate critical coupling with 26-dB on-resonance extinction and a matched dual-taper add–drop filter with less than 0.5% scattering loss and near-unity power transfer (on-resonance) between a fiber taper 12 and a micro-cavity resonator 6, where the resonator is a microsphere resonator 7.

A laser of the present invention has been constructed and tested in the laboratory, and is described more fully below. It will be appreciated that this embodiment is but one of many embodiments of the invention disclosed and claimed herein and is described as the currently known best mode of the present invention rather than as a limitation of the invention itself.

In this embodiment and referring to all of the figures generally, a fiber taper 12 is placed in contact with Er:Yb-doped phosphate glass microsphere 9, to form a compact, low-threshold 1.5 mm wavelength fiber laser source. A single fiber taper 12 is used to guide the pump 20 laser beam to the surface of the microsphere 9, resonantly couple the pump 20 into the sphere 9, and then collect the resulting laser emission. The use of a fiber taper 12 not only provides an efficient input and

output coupling port but also plays an important role in producing single-mode lasing. Finally, the fiber taper 12 forms a natural backbone for connecting a series of different active and passive micro-cavity devices, with each device addressing a different wavelength signal. These additional micro-cavity devices can be resonators, modulators, add/drop filters, slicers, or any other device which can optically connected to the fiber waveguide 5, preferably through the fiber taper 12 or one or more additional fiber tapers on the fiber waveguide 5 so as to make such connections without breaking the fiber waveguide 5.

The microspheres used in this embodiment were formed from phosphate glass heavily doped with Yb (20% by weight) and Er (0.5%). Kigre QX/Er phosphate glass has a transformation temperature of 450° C and a refractive index of 1.521 at 1.5 μm. Absorption that is due to the $F_{5/2}$-$F_{7/2}$ transition of the Yb^{3+} ions is strongly peaked around 976nm (±5 nm), with a value of $\propto$= 4-5 cm^{-1} (2 X 10^3 dB/m). The $F_{7/2}$ level of Yb^{3+} resonantly couples to the Er^{3+} $I_{11/2}$ level, which then relaxes to the $I_{13/2}$ level. The 1.5-μm lasing transition is between the ground-state $I_{15/2}$ level and the $I_{13/2}$ excited-state level of Er^{3+}, with a fully inverted gain per unit length exceeding 200 dB/m in the 1500 nm band.

Fabrication of the microspheres and the fiber tapers is discussed in the references cited above and incorporated herein. In summary, a small piece of the phosphate glass is melted in a crucible. With the phosphate still molten, the tip of a silica fiber taper, which has a higher melting point, is placed into the melt. As the silica "stem" is extracted, a small phosphate taper is formed on the end of the silica taper. A CO_2 laser is used to melt the end of the phosphate taper, forming a spheroid

under surface tension. The silica fiber stem is finally placed in a fiber chuck and used as a handling rod to control and position the phosphate sphere. It is important to carefully control the temperature of these operations and to cool the sphere quickly in a manner which avoids crystallization of the phosphate in the spheroid to an extent which would interfere with the reflective properties of the spheroid as a micro-cavity optical resonator.

The fiber tapers for this embodiment were formed by taking standard telecommunication 125 μm diameter silica fiber, heating a short region with a torch, and then slowly pulling the fiber ends to form an adiabatic taper region. In order to provide efficient coupling between the fiber taper 12 and the microsphere, a fiber taper diameter must be tailored for each different sphere size and WG mode of interest as described above. Fine tuning of the coupling can further be performed by changing the position of the sphere relative to the taper waist.

The resonant modes of nearly spherical dielectric particles can be classified according to their polarization index p, radial mode number n, and angular mode numbers l and m. Of special interest in this embodiment are the WGM resonances, *i.e.*, those with small radial mode numbers and large angular mode numbers. Excitation of WGMs within glass microspheres 7 via a fiber-taper 12 coupling has several distinct advantages. Most important of these is direct coupling to and from the optical fiber. In addition, alignment is built in, fabrication is relatively simple, and as discussed above, index matching between the fiber taper 12 and the diameter of the WGMs of the microsphere 9 is possible.

A magnified image of a coupled fiber taper microsphere is shown in Figure 3. For the microsphere laser of the present embodiment, the diameter and eccentricity were determined by analysis of its resonant mode structure at 1.5 μm. The measured WG mode free-spectral range in l (FSR_l) for this microsphere is 1.1 THz (8.7 nm) at 1.5 μm, giving a diameter of 57 μm. The measured free-spectral range in m is 13 GHz for $|m| \approx l$, with the resonant frequencies increasing with decreasing m value. This corresponds to a slightly oblate microsphere with an eccentricity of 2.4%. The pump wave in this embodiment is launched from a 980 nm wavelength, narrow-line width (< 300-kHz), tunable external-cavity laser into the fundamental mode of the fiber taper.

As discussed above, this embodiment also maximizes the efficiency of the pumping of the microsphere 9 by providing a good match between the fundamental mode of the fiber taper 12 and the WG modes of the sphere 9 and by matching the input coupling strength to the round-trip resonator loss (*i.e.*, critical coupling). Owing to the large absorption within the microsphere 9 at the pump band and the subsequent large round-trip microsphere resonator loss, maximum power transfer is obtained for the fundamental WG modes ($|m| = l$), as the spatial overlap with the fiber taper 12 is highest for the equatorial modes, resulting in higher input coupling strengths. For this sphere, a taper diameter of 1.75 micrometers was used to phase match and selectively excite the lowest-order (n= 1,2) fundamental WG modes of the sphere 9.

The pump volume within the micro-sphere can be obtained from images of the visible photo-luminescence. The green emission is due to spontaneous emission from the up converted $F_{9/2}$ level to the ground state of Er^{3+} and traces the path taken by the 980 nm pump wave within the sphere 9.

The image in Figure 6 shows a ring encircling the equator of the sphere. This equatorial ring corresponds to resonant pumping of a near fundamental WG mode. For this taper–sphere combination, and with resonant pumping of an equatorial WG mode, the scattering loss of the taper–sphere junction is less than 5% (as measured by the off-resonance transmission), and roughly 85% of the pump power is absorbed by the microsphere.

Lasing in the microsphere 9 is rather complex, owing to the large number of high-Q modes that are present in the sphere 9, the spatial selectivity of the pump 20, the loading of the sphere 9 as a result of the taper 12, the large spectral gain bandwidth, and the variations in the emission and absorption cross sections versus wavelength in the phosphate materials. For this reason other resonator geometries such as disks, rings or racetracks may be preferable to obtain a simplified resonator spectrum.

Depending on the gain region within the sphere, lasing occurred at wavelengths ranging from 1530 to 1560 nm in both multimode and single-mode fashion. By adjusting the taper 12 contact position on the sphere 9 and the pump 20 wavelength, it is possible to switch between multi-mode and single-mode lasing action. Single-mode lasing was obtained in this embodiment by tuning the pump wavelength to a fundamental WG mode resonance that produced a narrow equatorial-ring gain region. A typical single-mode lasing spectrum (as collected by the taper 12) for an equatorial-ring pump region is shown in Figure 7. To resolve the fine spectral features of the laser (different m modes) a high-finesse (~10,000) scanning Fabry–Perot cavity with a spectral resolution of a few megahertz was used to obtain the spectra shown in the inset of Figure 8. The microsphere of this

embodiment of the present invention will lase on a single m WG mode over the entire pump range depicted in Figure 8.

This embodiment of the present invention was also self-pulsing under the pump conditions identified herein, with a period of roughly 15 ms and a pulse width of 500 ns. Instability in the output of this embodiment can be linked to the large unpumped highly absorbing regions within the sphere 9 and the nonlinear dynamics associated with absorption saturation. A plot of the laser power collected in the taper 12 versus the total pump power absorbed and scattered by the presence of the sphere 9 (L_{out} - L_{in}) is shown in Figure 8. The lasing threshold for this embodiment in this configuration is estimated at 60μW, and the laser 22 can reach an output power of 3μW while remaining single mode. A collected power as high as 10μW was obtained in a single line at higher pump power, although the laser 22 was multimode. Given that this embodiment and configuration used the same taper 12 as was used to couple in the 980-nm pump power in the earlier described embodiment, to couple out the 1.5 μm laser power from the sphere 9, and since the taper was designed to phase match at the 980 nm pump wavelength to reduce the lasing threshold, the laser emission of this embodiment is not optimally collected by the taper 12. A dual-taper system, as is described earlier and in the Cai and Vahala reference above identified, could be employed to likely improve the differential output efficiency.

A further embodiment is the use of multiple resonators on a single fiber waveguide 5. This ability to cascade a series of devices is illustrated in Figure 9, where two phosphate glass microspheres 21, 23 are positioned along a single fiber taper, one after the other. The micro-cavity

devices can be the same or different sizes, depending on what the use and purpose the cascading is intended to achieve. Figure 9 shows a taper with two different-sized microspheres 21, 23 attached. The laser shown in Figure 9(a) has a wavelength of 1535 nm; the laser shown in Figure 9(b) which has a second microsphere 23 placed in contact with the fiber taper, a second laser line at 1533 nm appears. Thus, utilizing multiple resonators in a single fiber can be used to create a laser array.

Each of the characteristics in the present invention are believed to be new and unique, and are not found in the prior art. While the implementations described below are directed to embodiments of a laser which utilize a tapered fiber and a microsphere resonator, it will be understood by those skilled in the art that such configurations and/or combinations are merely embodiment of the present inventions. Thus, none of the embodiments are intended to be limitations on the scope of the invention described herein and set forth in the claims below.